Modeling *and* Simulation *of* Discrete-Event Systems

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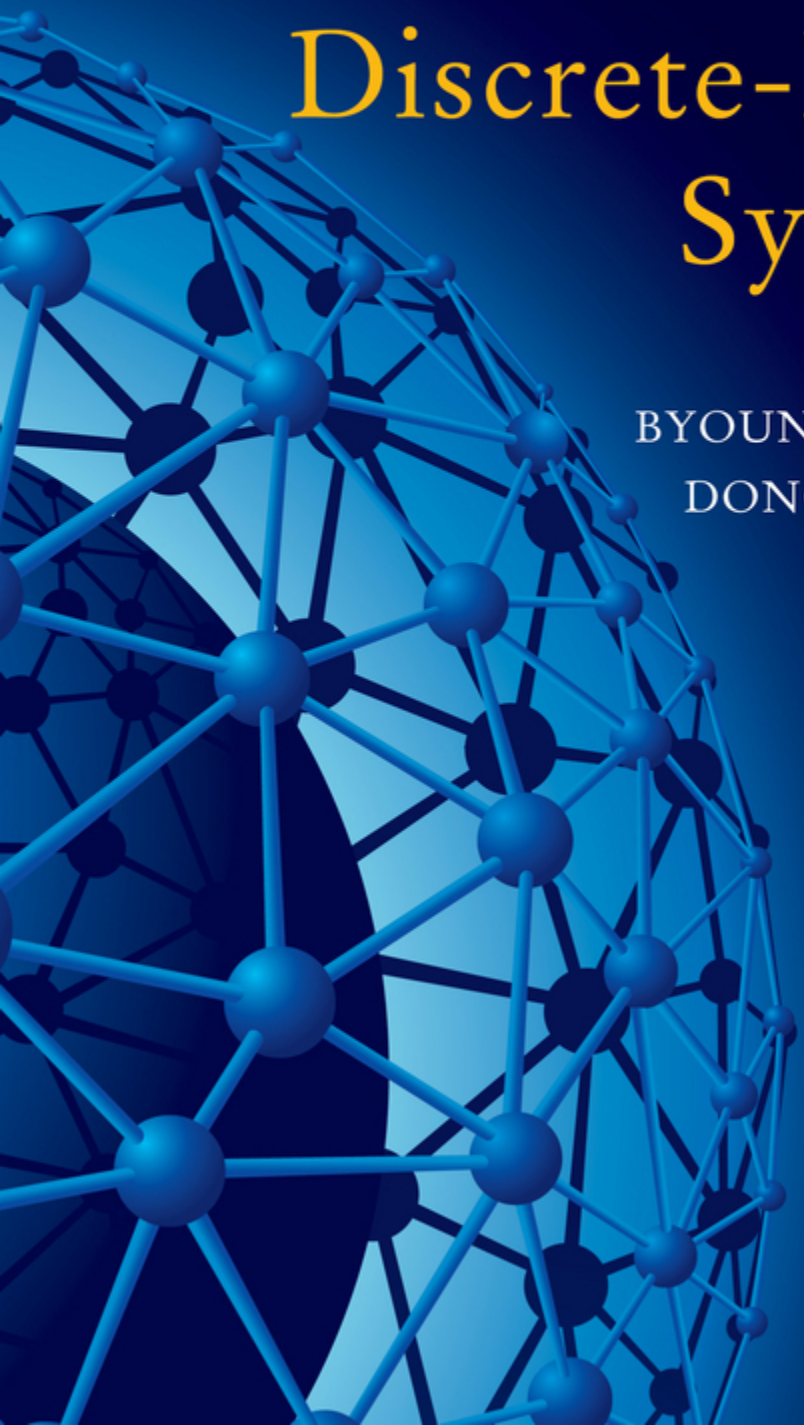
DONGHUN KANG



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MODELING AND SIMULATION OF DISCRETE-EVENT SYSTEMS

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Cover image: 08-17-09 © Mark Divers (iStock photo ID: 10295380)

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

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Library of Congress Cataloging-in-Publication Data:
Choi, Byoung Kyu, 1949–
Modeling and simulation of discrete-event systems / Byoung Kyu Choi, Donghun Kang.
pages cm
Includes index.
ISBN 978-1-118-38699-6 (cloth)
1. Discrete-time systems–Simulation methods. I. Kang, Donghun, 1981– II. Title.
T57.62.C377 2013
003'.83–dc23
2013013970

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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Online Supplements

Numerous supplemental materials including software downloads are provided on the official website of the book at http://VMS-technology.com/book. The supplemental materials are grouped into (1) M&S practices with commercial simulators, (2) developing your own dedicated simulators, and (3) integrated simulation of electronics Fabs. The commercials simulators covered are an event-based simulator SIGMA®, an activity-based simulator ACE®, a state-based simulator SGS®, and an entity-based simulator Arena®.

PREFACE

This book provides comprehensive, in-depth coverage of modeling and simulation (M&S) of discrete-event systems (DESs). Here, the term *M&S* refers to computer simulation, with an emphasis on modeling real-life DESs and executing the models. The current state-of-the-art in DES M&S is a result of the breakthroughs in the following areas: (1) activity-based modeling formalism pioneered by K.D. Tocher in late 1950s; (2) the advent of process-oriented simulation languages, such as GPSS and SLAM, in the early 1970s; (3) state-based modeling formalism, or DEVS, founded by Bernard Zeigler in the mid-1970s; and (4) event-based modeling formalism as matured by Lee Schruben since the early 1980s.

There exists at least one classic textbook in each area—a textbook on activity-based modeling by Carrie, a few books on state-based (DEVS) modeling by Zeigler, a textbook on event-based modeling by Schruben, and a few books on process-oriented languages such as Arena® and ProModel®. In addition, there are quite a few books focusing on statistical notions of computer simulation. The researchers in each area advocate their own views as central to DES M&S. Only a couple of books (e.g., Fishwick) propose an integrated model engineering framework.

This book presents an integrated M&S framework covering all four DES M&S breakthrough areas. It is a product of 30 years of teaching at KAIST, as well as sponsored research and development projects at the authors' lab at KAIST, VMS (virtual manufacturing system) Lab, which has been a government-endowed National Research Lab since 1999. In particular, the practice-oriented theme of this book is a result of the authors' decade-long experience in developing simulation-based scheduling (SBS) solutions for Samsung Electronics and other companies in Korea. Virtually all the Samsung's semiconductor fabrication plants (Fabs) and flat panel display (FPD) Fabs are run utilizing solutions originated by the authors' lab, and upgraded and supported by a spin-off venture company.

This book is divided into three parts: Part I, *Basics of System Modeling and Simulation*; Part II, *Fundamentals of Discrete-Event System Modeling and Simulation*; and Part III, *Advances in Discrete-Event System Modeling and Simulation*. Parts I and II are designed as a primary textbook for an undergraduate level M&S course in Industrial Engineering, Computer Science, and Management Science. With Part III, it is designed as a graduate-level course. This book comprehensively covers the state-of-the art modeling formalisms

and execution algorithms in DES M&S thereby serving as a main reference for M&S researchers in academia. This book provides an easy-to-understand guide for simulation practitioners in industry using off-the-shelf simulators such as SIGMA® and Arena®. Finally, this book reveals a number of "secrets" for developing your own simulators: event graph simulator, ACD simulator, state graph simulator, and integrated Fab simulator—making it a valuable resource for M&S solution developers.

The book is largely self-contained, and few prerequisites are needed for understanding its main contents. However, some prior knowledge will help readers understand specific sections:

(1) Basic knowledge of statistics and probability (Chapter 3, Input Modeling);
(2) Basic knowledge of linear algebra (Chapter 8, Output Analysis and Optimization)
(3) Experience with computer programming (Sections on developing your own simulators, e.g. Sections 5.7 and 10.2).

Perhaps the most critical prerequisite for mastering this book is enthusiasm and commitment toward M&S. This book is about the art of M&S, and like other art forms, can only be mastered through persistent practice.

The authors wish to express their special thanks to Prof. K.H. Han of Gyeongsang National University for using part of this book in his class and providing valuable comments that led to its improvement; to Prof. I.K. Moon of Seoul National University and Prof. S.C. Park of Ajou University for their input during the early stage of writing this book; and to Prof. Lee Schruben of Berkeley for his encouragement and support. For developing sample models and exercise problems, and for executing "prototype" simulation models appearing in the book, we would like to thank our graduate students in the VMS Lab at KAIST, especially H.S. Kim, T.J. Choi, and E.H. Song.

Finally, Byoung Choi thanks his wife, Yong, and his son and best friend Samuel, for their support and encouragement. Donghun Kang thanks his parents for their loving care and support.

Byoung Kyu Choi
Donghun Kang

Daejeon, Korea, June 2013

ABBREVIATIONS

ACD	activity cycle diagram
AGV	automated guided vehicle
AMHS	automated material handling system
AON	activity-on-node
AQL	average queue length
AST	average sojourn time
ATM	automatic teller machine
ATT	activity transition table
AWT	average waiting time
BTO	bound-to-occur
CAL	candidate activity list
DES	discrete-event system
EFD	entity flow diagram
EG	event graph
EO	event object
EOS	end of simulation
Fab	Fabrication line (or plant)
FED	federation execution data
FEL	future event list
FIFO	first-in-first-out
FMS	flexible manufacturing system
FOM	federation object model
FPD	flat panel display
FSA	finite state automata
FSM	finite state machine
HLA	high level architecture
IFS	integrated factory simulator
LCD	liquid crystal display
LEL	local event list
LP	logical process
M&S	modeling and simulation
MCS	material control system
MDP	message delivery packet
MEL	move-type event list
MLE	maximum likelihood estimator
MS	mean square
MSR	message send request
OOEG	object-oriented event graph
P-ACD	parameterized ACD
PDM	process definition model
PEG	parameterized event graph
RSM	response surface methodology
RTD	real-time dispatcher
RTI	run time infrastructure
SG	state graph
SOM	simulation object model
SS	sum of square
TAG	time advance grant
TAR	time advance request
VE	virtual environment
WfMS	workflow management system

PART I

BASICS OF SYSTEM MODELING AND SIMULATION

We think by "constructing mental models and then simulating them in order to draw conclusions or make decisions." Thus, modeling and simulation (M&S) constitutes the central part of our thinking process. "I think, therefore I am" is a philosophical statement used by the French philosopher Descartes, which became a foundational element of Western philosophy. Therefore, if we combine the philosophical notion of thinking with the engineering definition of M&S, we may say that "we are engineers and scientists because we can model systems and simulate them." Furthermore, if our brain is not powerful enough to simulate a given complex system, we rely on computers to perform a computer simulation.

A dictionary definition of *simulation* is the technique of imitating the behavior of some situation by means of an analogous situation or apparatus to gain information more conveniently or to train personnel, while an academic definition of *computer simulation* is the discipline of designing a model of a system, simulating the model on a digital computer, and analyzing the execution output. In recent years, the term *modeling and simulation* (M&S) seems to be preferred to the term for computer simulation, with an emphasis on modeling. Part I of this book has two chapters, and it aims to provide the readers with a basic but comprehensive treatment of computer simulation.

Chapter 1, "Overview of Computer Simulation," will provide answers to the following basic questions in computer simulation:

1. What is a system?
2. What is computer simulation?
3. What is discrete-event simulation?
4. What is continuous simulation?
5. What is Monte Carlo simulation?
6. What are simulation experimentation and optimization?

Modeling and Simulation of Discrete-Event Systems, First Edition. Byoung Kyu Choi and Donghun Kang.
© 2013 John Wiley & Sons, Inc. Published 2013 by John Wiley & Sons, Inc.

Chapter 2, "Basics of Discrete-Event System Modeling & Simulation," aims to provide answers to the following basic questions in discrete-event system (DES) M&S:

1. How is a discrete-event simulation carried out?
2. What are modeling components and a reference model?
3. What is a discrete-event system modeling formalism?
4. What is a formal model and how it is specified?
5. What is the integrated framework of discrete-event system modeling?
6. How do we build and simulate an event graph or activity cycle diagram (ACD) model of a DES?
7. How is the M&S life cycle managed?

CHAPTER 1

Overview of Computer Simulation

The wise man is one who knows what he does not know.

—Tao Te Ching

1.1 INTRODUCTION

Richmond [2003] defines thinking as "constructing mental models and then simulating them in order to draw conclusions or make decisions." Namely, he defines thinking as mental simulation. When the situation is too complex to be analyzed by mental simulation alone, we rely on computer simulation. According to Schruben [2012], simulation models provide unlimited virtual power: "If you can think of something, you can simulate it. Experimenting in a simulated world, you can change anything, in any way, at any time—even change time itself."

Fishwick [1995] defines *computer simulation* as the discipline of designing a model of a system, simulating the model on a digital computer, and analyzing the execution output. In the military, where computer simulation is extensively used in training personnel (e.g., war game simulation) and acquiring weapon systems (e.g., simulation-based acquisition), the term *modeling and simulation* (M&S) is used in place of *computer simulation*. In this book, these two terms are used interchangeably.

The purpose of this chapter is to provide the reader with a basic understanding of computer simulation. After studying this chapter, you should be able to answer the following questions:

1. What are the common characteristics that lead to a conceptual definition of system?
2. What are the three types of systems?
3. What are the three subsystems in a feedback control system?
4. What are the three types of virtual environment simulation?

Modeling and Simulation of Discrete-Event Systems, First Edition. Byoung Kyu Choi and Donghun Kang.
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5. What are the three types of computer simulation?
6. What is the simulation model trajectory of a discrete-event system?
7. What is Monte Carlo simulation?
8. What is sensitivity analysis in simulation experimentation?

This chapter is organized as follows: Definitions and structures of systems are given in Section 1.2. Section 1.3 provides definitions and applications of simulation. The subsequent three sections introduce the three simulation types: discrete-event simulation in Section 1.4, continuous simulation in Section 1.5, and Monte Carlo simulation in Section 1.6. Finally, a basic framework of simulation experimentation is presented in Section 1.7.

1.2 WHAT IS A SYSTEM?

1.2.1 Definitions of Systems

Systems are encountered everywhere in the world. While those systems differ in their specifics, they share common characteristics that lead to a conceptual definition of a system. In Wu [1992], a *system* is defined as "a collection of components which are interrelated in an organized way and work together towards the accomplishment of certain logical and purposeful end." Thus, any portion of the real world may be defined as a system if it has the following characteristics: (1) it has a purpose or purposes, (2) its components are connected in an organized manner, and (3) they work together to achieve common objectives. A system consisting of people is often called a *team*. Needless to say, a mere crowd of people sharing no common objectives is not a team.

When defining a system, the concept of state variable plays a key role. A *state variable* is a particular measurable property of an object or system. Examples of state variables are the number of jobs in a buffer, status of a machine, temperature of an oven, etc. A system in which the state variables change instantaneously at discrete points in time is called a *discrete-event system*, whereas a system in which state variables change continuously over time is called a *continuous system*.

1.2.2 Three Types of Systems

Our universe, which is full of systems everywhere, may be viewed from the five levels of detail (Fig. 1.1): from the subatomic level to cosmological level. In the subatomic level, interactions among the components of a system are described using quantum mechanics, which is a physical science dealing with the behavior of matter and energy on the scale of atoms and subatomic particles. It is interesting to find that quantum mechanics is also used in modeling a system at the cosmological level [Mostafazadeh 2004]. Thus, a system in the subatomic level or cosmological level may be called a *quantum system*.

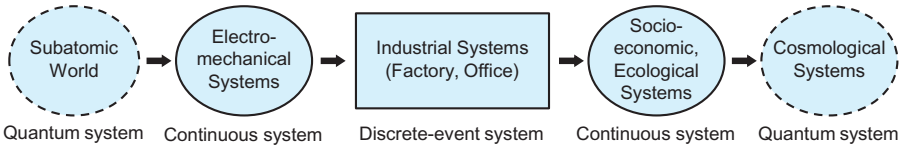

Fig. 1.1. Five levels of details of system definitions in the universe.

A system in the electromechanical level usually has components whose physical dynamics are described using differential equations of effort, such as force and voltage, and flow, such as velocity and current [Karnopp et al. 2000]. The behaviors of ecological systems and socioeconomic systems are usually described using differential equations of flow [Hannon and Ruth 2001]. As a result, these systems are called a *continuous system* or a *differential equation system*.

Systems in the middle level are industrial systems which are more conveniently described in terms of discrete events, and they are discrete-event systems. An event is an instance of changes in state variables. A special type of this system is a digital system such as a computer whose states are defined by a finite number of 0s and 1s.

1.2.3 System Boundaries and Hierarchical Structure

Everything in our world is connected to everything else in some way, which is known as the small world phenomenon [Kleinberg 2000]. Thus, in order to define a system, it is first necessary to isolate the components of the system from the remaining world and to enclose them within a system boundary.

A set of isolated components of primary interest is called a *target system*. The target system may have a number of subsystems, and it may be a subsystem of a higher-level system called a *wider system*. The wider system is separated from the external environment by a boundary [Wu 1992]. In summary, a typical system consists of a target system (composed of its subsystems) and a wider system (in which the target system is included). The system of interest consisting of a target system and its wider system is often referred to as a *source system*.

Most dynamic systems in engineering and management are feedback control systems. Key subsystems in a feedback control system are operational, monitoring, and decision-making subsystems. The operational subsystem carries out the system's tasks, and the monitoring subsystem monitors system performances and reports to the decision-making subsystem. The decision-making subsystem is responsible for making decisions and taking corrective actions. The relationships among the target feedback control system, its subsystems, wider system, and external environment are shown in Fig. 1.2 [Wu 1992]. For example, if your simulation study is focused on an emergency room of a hospital, the emergency room would become the target system and the hospital the wider system.

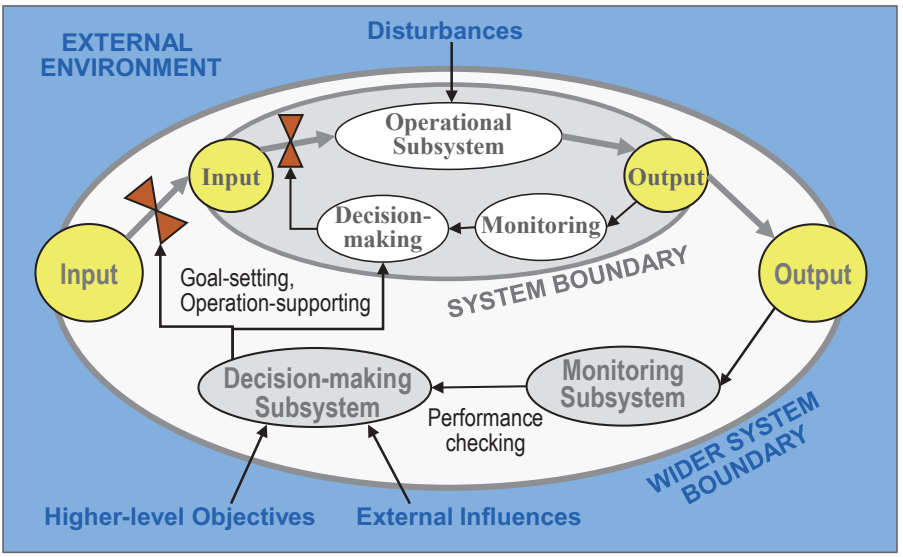

Fig. 1.2. Hierarchical structure of feedback control system.

The wider system influences the target system by setting goals, supporting operations, and checking performances. The target system is subject to disturbances from the external environment. In addition, the external environment provides the wider system with higher-level objectives and other external influences.

Exercise 1.1. Give an example of a feedback control system involving people and identify all the components of the system.

1.3 WHAT IS COMPUTER SIMULATION?

1.3.1 What Is Simulation?

A dictionary definition of *simulation* is "the technique of imitating the behavior of some situation by means of an analogous situation or apparatus to gain information more conveniently or to train (or entertain) personnel." "Some situation" in the definition corresponds to a source system, and an *apparatus* is a simulator. As elaborated in the definition, there are two types of simulation objectives: one is to gain information and the other is to train or entertain personnel. The former is often called an *analytic simulation* and the latter a *virtual environment simulation* [Fujimoto 2000].

The main purpose of an analytic simulation is the quantitative analysis of the source system based on "exact" data. Thus, the simulation should be executed in an as-fast-as-possible manner and be able to precisely reproduce the event sequence of the source system. An analytic simulation is often referred

Fig. 1.3. Examples of virtual environment simulation.

to as a *time-stamp simulation*. A virtual environment simulation is executed in a scaled real-time while creating virtual environments, and it is often referred to as a *time-delay simulation*. Shown in Fig. 1.3 are scenes from a war-game simulation and from a computer game.

An analytic simulation with human interaction is called a *constructive simulation*, and one without human interaction an *autonomous simulation.* If humans interact with the simulation as a participant, it is referred to as human-in-the-loop (HIL) simulation; if machines or software agents interact with the simulation, it is called a machine-in-the-loop (MIL) simulation. A virtual environment simulation without HIL/MIL is often called a *virtual simulation*; one with HIL only a *constructive simulation*; one with both HIL and MIL a *live simulation*. Figure 1.4 shows the classification of computer simulation.

1.3.2 Why Simulate?

Modeling and simulation is the central part of our thinking process. When the situation is too complex to be analyzed by mental simulation alone, we use a computer for simulating the situation. Let's consider the following situations:

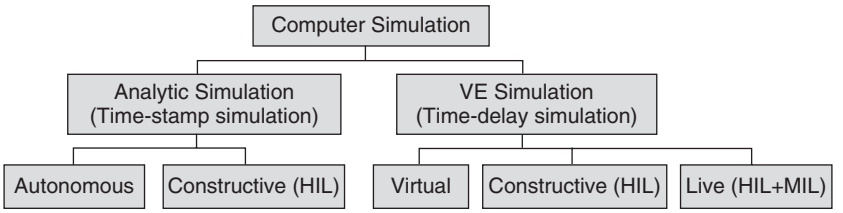

Fig. 1.4. Classification of computer simulation.

1. Finding optimal dispatching rules at a modern 300-mm semiconductor Fab
2. Evaluating alternative designs for hospitals, post offices, call centers, etc.
3. Designing the material handling system of a 3 billion dollar thin film transistor–liquid crystal display (TFT-LCD) Fab
4. Planning a wireless network for a telecommunication company
5. Evaluating high-tech weapons systems for a simulation-based acquisition
6. Designing or upgrading the urban traffic system of a big city
7. Evaluating anti-pollution policies to control pollutions in river systems
8. Evaluating risks in project schedules and financial derivatives

For the above real-life situations, simulation may be the only means to tackle the problems. In practice, simulation may be needed because experimenting with the real-life system is not feasible; your budget does not allow you to acquire an expensive prototype; a real test is risky; your customer wants it "yesterday"; your team wants to test several solutions and to compare them; you would like to keep a way to reproduce its performances later.

The simulation of a discrete-event system is called a *discrete-event simulation*, and that of a continuous system a *continuous simulation*. A class of computational schemes that rely on repeated random sampling to compute their results is referred to as *Monte Carlo simulation*. Among the above situations, Situations 1–6 are concerned with a discrete-event simulation. Situation 7 is concerned with a continuous simulation and Situation 8 with a Monte Carlo simulation.

1.3.3 Types of Computer Simulation

As depicted earlier in Fig. 1.1, the dynamic systems in the universe can be classified into five levels and three types. The three types of dynamic systems are: (1) discrete-event systems, (2) continuous systems, and (3) quantum systems. Thus, it is conceivable that there is one type of computer simulation for each system type. Discrete-event simulation and continuous simulation are widely performed on computers, but the direct simulation of quantum systems